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Probability of Sediment Yields from Surface Erosion on Granitic Roadfills in Idaho

Walter F. Megahan,* Stephen B. Monsen, and Monte D. Wilson

ABSTRACT

A series of 29 bordered plots, 1.8 m wide by 4.6 m long, was used to measure sediment yields from granitic roadfills on forest roads in the mountains of Idaho. Slope gradients on the plots ranged from 34 to 41°. Sediment yield data for the snowfree season were collected for 3 yr following road construction. Various site factors were tested by regression analysis for their effects on sediment yield, but only ground cover density and snowfree period rainfall erosivity were statistically significant. Analysis of 22 yr of snowfree period rainfall erosivity data showed that erosivity was log-normally distributed and established the parameters for the probability density function. These data, coupled with the prediction equation from the regression model, were then used in a Monte Carlo simulation model to define the probability of occurrence of sediment yields from granitic roadfills given various levels of ground cover density. Recently published studies that update the slope gradient and slope length components of the Universal Soil Loss Equation are used to extrapolate the results of the present study to all lengths and gradients of granitic roadfills. A discussion of the application of the study results is presented.

Granitic soils in the Western United States are noted for high erodibility because of their relatively coarse texture and lack of cohesion. For example, André and Anderson (1961) used surface aggregation ratio as an index of erodibility for soils collected at 168 sites in California. Soils derived from granitic rocks were the most erodible of the eight geologic parent materials sampled.

Concern for soil erosion on granitic soils is especially high in the Idaho Batholith, a 40 000 km^2 expanse of granitic rocks in central Idaho (Fig. 1). Extensive timber resources in this mountainous region create a demand for logging and associated road construction. However, accelerated surface erosion on roadfills has been severe in the past (Haupt et al., 1963; Bethlahmy and Kidd, 1966; Boise State University, 1984) with maximum sediment yields sometimes exceeding 450 Mg/ha the first winter after construction. Sedimentation caused by excessive road erosion has led to serious adverse cumulative effects to valuable anadromous fishery resources (Seyedbagheri et al., 1987). Several studies have shown that erosion control measures on granitic roadfills can effectively reduce erosion (Megahan, 1974; Megahan et al., 1990, unpublished manuscript). However, all past work evaluated average long-term treatment success, so there was no way to relate treatment to changes in climatic conditions. Also, no attempts were made to relate erosion rates to site factors that might influence erosion rates.

W.F. Megahan, Intermountain Research Station, Forest Service, USDA, 316 East Myrtle Street, Boise, ID 83702; S.B. Monsen, Intermountain Research Station, 735 North 500 East, Provo, UT 84606; and M.D. Wilson, Dep. of Geology and Geophysics, Boise State Univ., Boise, ID 83725. Received 28 Feb. 1990. *Corresponding author.

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The objective of this study was to test whether the risk of sediment yields from erosion on granitic roadfills could be evaluated using precipitation and fill slope characteristics for untreated fill slopes as well as fill slopes treated with various erosion control measures. A successful prediction model will provide a useful tool for forest land managers who are charged by law to evaluate the cumulative effects of alternative land management activities.

THE STUDY AREA

The study site is in the headwaters of the Silver Creek drainage, a tributary to the Middle Fork of the Payette River in southwestern Idaho. Coordinates of the approximate center of the study area are 44°25′N lat, and 115°45′W long (Fig. 1).

Annual precipitation on the study area averages about 890 mm with most occurring during the winter months. Summers are hot and dry with occasional, localized convective storms. More generalized frontal type rains are common in May and June and in the fall in late September and October. About 65% of the annual precipitation occurs as snowfall that produces an average maximum snowpack water equivalent of about 55 cm.

Bedrock at the study site is primarily coarse-grained quartz monzonite and is typical of a large part of the central and southern portions of the Idaho Batholith. Soils are weakly developed with A horizons ranging from 5 to 25 cm thick overlying moderately weathered granitic parent material. Soil textures are loamy sands to sandy loams, and depth to bedrock is usually less than 100 cm. Shallow soils less than 20 cm deep are common on ridges and south slopes, and scattered outcrops of granitic bedrock are found in the upper elevations of the watersheds. Four types of soils occur on the study watersheds depending on the gradient and aspect of the hillslopes. Sandy-skeletal mixed Typic Xerorthents predominate on south slopes. Sandy-skeletal, mixed Typic Cryorthents; sandy-skeletal, mixed Typic Cryoborolls; and mixed Alfic Cryopsamments are found at other locations (Clayton and Kennedy, 1985).

Hillslopes in the area are steep, ranging from 15 to 40 degrees, and are highly dissected. Vegetation varies primarily in response to changes in slope aspect and soil properties and is characterized by two principal vegetation habitat types (Steele et al., 1981): Douglas-fir/white spirea, ponderosa pine phase [*Pseudotsuga menziesii* (Mirbel) Franco/*Spiraea betulifolia*, *Pinus ponderosa* Dougl. ex. P. & C. Laws. phase] and Douglas-fir/ninebark, ponderosa pine phase [*Pseudotsuga menziesii* (Mirbel) Franco/*Physocarpus malvaceus* (L.) Maxim., *Pinus ponderosa* Dougl. ex. P. & C. Laws. phase]. Timber stands are dominated by approximately equal volumes of mature and over-mature ponderosa pine and Douglas-fir.

The study was conducted on a road constructed across three study watersheds within the Silver Creek study area. Construction began in June and was completed by November 1980. Most study plots were on fill slopes within the No Name drainage; the remainder were on the section of road west of the No Name drainage divide (Fig. 1). Individual roadfills were randomly selected for plot locations. Because of the steep gradient of the hillslopes in the area, roadfills were designed for construction at either 1.33:1 or 1.5:1 gradients (horizontal/vertical) to minimize fill slope lengths. Drainage from the road surface was carefully controlled so

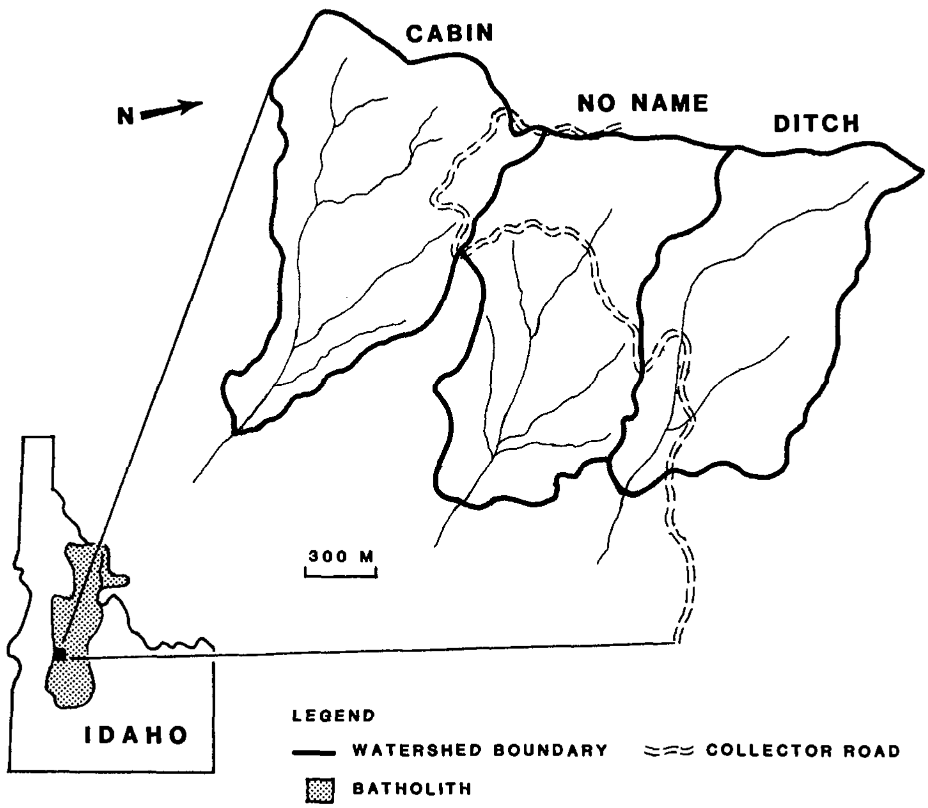

Fig. 1. Location map and detail of the study Silver Creek area.

that runoff from the road surface was not allowed to flow over the surface of fills once the road construction was completed.

DATA COLLECTION

Earlier studies (Megahan, 1974; King, 1984) showed that surface erosion rates on forest roads are greatest immediately after disturbance and decrease rapidly over time. This work suggests that erosion control treatments must be designed to accomplish two things: (i) provide site protection for the early, high erosion period when vegetation has not yet had a chance to become established (using mulches and other surface amendments); and (ii) provide for long-term erosion control when surface amendments are no longer effective (by establishment of vegetation). Ideally, a combination of the two measures should optimize erosion control over the long run.

A plot study was designed to evaluate all three possibilities using a variety of erosion control measures (Megahan et al., 1990, unpublished manuscript) that included (i) surface amendments alone, (ii) revegetation measures alone, (iii) combinations of both revegetation and soil amendments, and (iv) untreated control plots. Treatments included some practices common to the area plus some new techniques such as sprigging and use of a steep slope planter (Pickett et al., 1980). The erosion control measures included in the present study are described in Table 1.

Dimensions of the rectangular plots were 1.8 m by 4.6 m for a total area of 8.3 m^2 with the long axis oriented up and down hill. The plots were bordered on all sides with 2.5 cm by 20 cm lumber. A collection trough 15 cm wide by 15 cm deep was used to collect sediment at the bottom of each plot. Boards were installed at 45° at the top of the plots to deflect rocks rolling downslope from above. Details of the plot construction procedure are summarized in a report by the Boise State University (1984). Each plot was at least 3 m downhill from the upper end of the fillslope and at least 3 m from adjacent erosion plots. On plots where surface treatments were used, the 1.8 m wide plots were located in the center of 6.1 m wide treated strips oriented up and down the slope. Thus, a buffer strip of approximately one plot width was available on each side of a plot. Gradients of the fillslope erosion plots ranged from 34 to 41°.

The original study plan called for installation of all post-construction erosion control measures and study plots as soon as the road construction was completed. Unfortunately, the road construction was delayed and it was impossible to begin installation of the study until October 1980. All erosion control treatments were in place by early November. However, only eight of the plots for the present study could be completed before snow and frozen soil conditions made it impossible to continue. Plot construction resumed following spring snowmelt in 1981, and an additional 21 plots were completed by July for a total of 29 plots. Ladders were placed on the fillslope surfaces to support scaffolds so that treated surfaces were not disturbed by trampling in situations where plots were constructed after the erosion control treatments were applied.

Sediment yields from study plots were collected in the spring following snowmelt in May or early June, and in the fall on or around the end of September beginning in 1981 and continuing in 1982 and 1983. However, only about 25% of the plots had been constructed at the time of the spring 1981 data collection, so complete data sets were available for analysis for three summer and only two winter collections. An additional loss of data occurred during the winter of 1982 when two treated plots were irreparably damaged by a single 250 m^3 mass failure on a fillslope. Sediment samples were oven-dried and weighed, and selected samples were analyzed for particle size distribution.

A network of five recording raingauges was installed along

Table 1. Erosion control treatments used on roadfill study plots.

		Type treatment†	Number of plots
1.	Straw,‡ crimp,§ seed,¶ fertilizer,# transplant††	3	2
2.	Straw,† polymer,‡‡ seed,¶ fertilizer,# transplant,††	3	2
3.	Steep slope seeder§§	1	2
4.	Steep slope seeder,§§ transplant††	1	2
5.	Hydromulch,¶¶ seed,¶ fertilizer,# transplant††	3	4
6.	Hydromulch,¶¶ seed,¶ fertilizer#	3	2
7.	Sprig,## transplant††	1	2
8.	Polymer,‡‡ seed,¶ fertilizer,# transplant††	3	2
9.	Sprig##	1	2
10.	Straw,‡ crimp§	2	2
11.	Hydromulch¶¶	2	1
12.	Untreated control†††		3
13.	Straw,‡ polymer‡‡	2	1
14.	Polymer‡‡	2	2

† 1 = revegetation alone, 2 = surface amendment alone, 3 = combination of 1 and 2.
‡ *Straw*—Straw evenly placed on the slope by hand at a rate of 4500 kg/ha.
§ *Crimp*—Rolling of placed straw with a sheep's foot roller.
¶ *Seed*—Application of nine assorted grasses plus alfalfa and clover with a hand spreader at a rate of 125 kg/ha. When used in conjunction with hydromulching, seed was added to the fiber-water mixture and sprayed on the slope.
# *Fertilizer*—Application of N-P-K at rates of 70 to 35 kg/ha, respectively, using either a hand spreader or added to the hydromulch mixture and sprayed on the slope.
†† *Transplant*—Hand planting of five shrub species plus ponderosa pine at a 1.2-m spacing.
‡‡ *Polymer*—Application of a liquid commercial erosion control product designed to adhere to the soil surface and reduce erosion. Applied by spraying at a rate of 1879 L/ha as an emulsion with water.
§§ *Steep slope seeder*—A mechanical device designed to rake miniterraces on the slope, drop seed, and fertilizer in the furrow and incorporate the seed into the soil by rolling with small mesh drums. The device is placed along the fill slope with the use of a gradall.
¶¶ *Hydromulch*—Application of a cellulose fiber to the slope at a rate of 2240 kg/ha. Fiber is mixed with water and sprayed on the slope.
Sprigging—Hand transplanting of rhyzomes of Louisiana sagebrush (*Artemisia ludoviciana* Nutt.) at 0.3-m spacing.
††† *Control*—No treatment was used. Erosion plots were kept free of volunteer vegetation by occasional spraying with herbicide.

the road to measure rainfall intensities throughout the elevation range of the road. In addition, two weather stations are located at the elevation extremes along the road.

Observations confirmed the fact that erosion is directly proportional to rainfall intensity and runoff rates. Wischmeier and Smith (1958) developed a rainfall erosivity index (EI) defined as the storm kinetic energy (a function of rainfall intensity) times the maximum 30-min rainfall intensity to integrate the effects of raindrop impact and potential runoff. We developed EI values for all storms occurring during the study using the rainfall intensity data from the five recording raingauges along the road. There was no good basis to extrapolate the EI values from the five raingauge sites along the road to individual study plots, so the EI data for the raingauges were averaged by days and accumulated for the erosion measurement periods applicable to each of the individual study plots. However, EI values are meaningless during the long winter periods of snow cover (Cooley et al., 1988). Accordingly, long-term (since 1975) data from the weather stations, including snow course, raingauge, and recording hygrothermograph data, were used to develop a degree day model of snow accumulation and melt. The model was used to define the beginning and end of the snowfree period in the spring and fall.

On all study plots except the plots treated by sprigging, ground cover density data were collected on five 0.19 m^2 sample plots located randomly within each erosion plot. Two randomly located plots, 1.0 m^2 in size, were used to sample the sprigged plots. Plot locations were permanently marked so data could be collected at the same locations over time. All plots were sampled in June and August 1981 and in August of subsequent years. Data collection included ocular estimates of the percentage of ground covered by bare soil, litter, mulch, and the vegetation canopy projected to the soil level, along with plant density and species composition.

Additional site data including elevation, slope gradient, and slope azimuth were collected for each study plot. Slope gradient and azimuth were used to calculate potential direct beam solar radiation for the plots (Buffo et al., 1972).

Most of the embankment material used to construct the roadfills was derived from the underlying granitic regolith rather than the residual soils on the hillsides, because the hillsides are steep and the residual soils are shallow. A total of 33 samples were collected from the top 10 cm of the surface of roadfills in the area for sieve analyses of particle size. Average particle size for the samples by size classes was as follows: silt and clay (<0.063 mm)—5%, fine to medium sand (0.063 to <0.5 mm)—38%, coarse sand (0.5 to <2.0 mm)—34%, fine to medium gravel (2.0 to <19.0 mm)—21%, and coarse gravel (19.0 mm and larger)—2%.

RESULTS

Factors Affecting Sediment Yields

Stepwise multiple regression was used to evaluate the effects of site factors on fillslope sediment yields. Data used for the analysis included all five complete measurement periods except in the case of the two treated plots that were destroyed in 1982 and for individual measurements where field observations indicated erroneous information. We intentionally omitted what little data we had from the first over-winter period from the analysis, because there was clear evidence that a major part of the erosion was caused by mass erosion of the unconsolidated fill material. Small scale liquification of surface materials was common both in and outside the erosion plots. No such micro scale mass erosion was observed during subsequent visits to the area. Rather, erosion appeared to consist entirely of surface erosion processes including rilling, raindrop splash, and dry creep. The theoretical basis for modeling surface and mass erosion processes of these materials is entirely different. Thus, there is no justification for including the data for the first over-winter period in the analysis.

With the missing data removed, the total sample size was 121. Independent variables tested in the analysis included elevation, slope gradient, slope azimuth, direct beam solar radiation, ground cover density, and erosivity index. Ground cover density was expressed as 100 minus percentage bare soil and provides a measure of ground cover density similar to that used by Packer (1951) and Meeuwig (1969) on granitic soils in Idaho. The mean, range, and standard deviation for all variables are summarized in Table 2. The frequency

Table 2. Range mean and standard deviation of study variables.

Variable	Range		Mean	SD
	Minimum	Maximum		
Erosion, Mg/ha yr	0.2	94.8	5.5	12.1
Vegetation cover density, %	1	93	45	32
Erosivity index, MJ mm/ha h	19	452	160	151
Elevation, m	1525	1683	1583	51
Slope gradient, degrees	34.0	41.0	37.3	1.8
Slope azimuth, degrees	40	332	151	78
Direct beam radiation, kcal cm^2/yr	92	237	189	54

of occurrence of roadfill sediment yield data such as collected in this study has been shown to be highly skewed to the right, rather than normally distributed (Megahan and Kidd, 1972; Megahan, 1978). Accordingly, $\log_{10}$ transformations were used to normalize the data.

Only two variables, ground cover density (GCD) and snowfree period rainfall erosivity (EI), were statistically significant ($P < 0.01$). The remaining variables including fillslope gradient, slope aspect, elevation, and direct beam solar radiation were not statistically significant ($P > 0.05$). The prediction model is of the form:

$$\log_{10}E = 0.7531 \times \log_{10}\mathrm{EI} - 0.6166 \times \log_{10}\mathrm{GCD} - 0.35495 + e \quad [1]$$

and has r^2 value of 0.55 and a standard error of 0.382 log units.

where

E = total sediment yield for the measurement period (Mg/ha yr)

EI = total erosivity index for the measurement period for snowfree conditions (MJ mm/ha h)

GCD = ground cover density (%)

e = an error term with a mean of zero and variance of 0.146 log units

Evaluating Sediment Yield Probabilities

The sediment yield prediction model utilizing GCD and EI provides us with the opportunity to evaluate the variability of sediment yields in response to variations in EI. Long-term EI data are not presently available for the Silver Creek study area. However, such data were available from the USDA-ARS study site at Reynold's Creek Experimental watershed, about 125 km to the southwest of the present study site. Cooley et al. (1988) presented average values for 22 yr of annual snowfree EI data for six raingauges at Reynold's Creek, ranging from 1184 to 2164 m in elevation and from 244 to 1144 mm in annual precipitation. The ARS graciously provided the snowfree EI data for all 22 yr of record for the Reynold's Creek raingauges. An analysis of variance test showed no statistically significant differences ($P > 0.05$) between EI data from the Silver Creek and Reynold's Creek study areas for the duration of the present study. The probability of a type 2 error is high for such a test because of the large variance in the EI data, so the ANOVA results are not conclusive proof that there are no differences in EI values between the two study areas. However, the elevations and the corresponding annual precipitation for the five raingauges at Silver Creek fall within the ranges of elevation and annual precipitation for the six raingauges at Reynold's Creek, and both areas are influenced by the same general air mass movements. Considering all of the above, we concluded that the annual snowfree erosivity data at Reynold's Creek are applicable at Silver Creek.

Actual and log-transformed values of the annual snowfree erosivity data from each gauge at Reynold's Creek were tested to see if the data represented a nor-

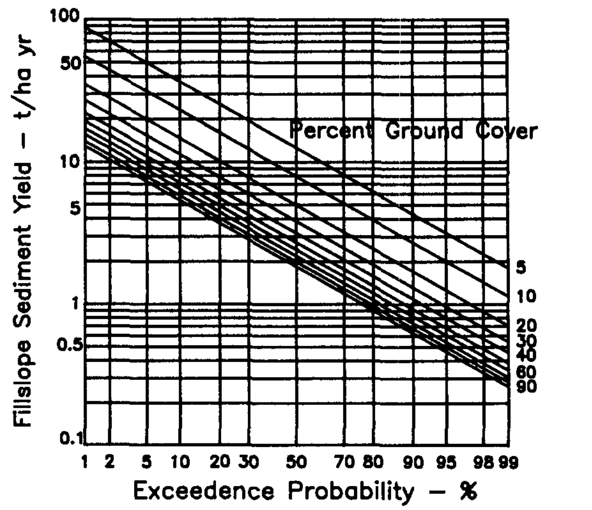

Fig. 2. Probability of occurrence of sediment yields from granitic roadfills as a function of ground cover density.

mal probability density function (PDF) using the Martinez-Iglewicz (1981) test. Nonnormal PDF values were found for five of the six gauges for the untransformed EI data ($P < 0.05$). However, none of the log transformed data exhibited a nonnormal PDF, so the log normal PDF appears to provide an adequate representation of the snowfree EI data on Reynold's Creek. Dunne and Leopold (1978) reported that the log normal PDF is often appropriate for describing EI data. Regression analysis showed that neither the mean nor the standard deviation of the 22 yr of log transformed EI data for the six raingauges on Reynold's Creek was related to gauge elevation. Thus, we conclude that the overall average of the mean and standard deviation of log transformed EI values in Reynold's Creek represent any of the gauges regardless of elevation and that these values are appropriate to represent the statistical properties of annual snowfree period EI values in Silver Creek.

Given the mean and standard deviation for the log normally distributed annual snowfree period EI values in Silver Creek and Eq. [1], it is possible to estimate annual sediment yields from road fillslopes for various values of ground cover density using Monte Carlo simulation procedures (Haan, 1977). However, Eq. [1] was developed using snowfree EI values for data collection periods rather than total annual snowfree period EI values. The EI values used to derived Eq. [1] ranged from 19 to 452 MJ mm/ha h compared to an average range of 51 to 494 MJ mm/ha h for the annual snowfree EI values for the six raingauges at Reynold's Creek. Because of the large overlap in the two sets of EI data, we felt Eq. [1] could be used to predict annual roadfill sediment yields based on annual snowfree period EI data.

Inspection of plots of deviations from regression for Eq. [1] suggested that the error term was additive when log transformations of the model variables were used. Accordingly, the simulation included a simulated, additive error term based on the mean and standard deviation of e. A total of 5000 estimates of annual sediment yield was generated for each of 10 ground cover density classes ranging from 5 to 90% and the mean and standard deviation of each set of simulated values was used to determine a cumulative probability density function for predicted annual sediment yields. The procedure described by Baskerville (1972) was used to convert sediment yield values from log to standard units to avoid bias. Applying this procedure to the data in the present study, the $\log_{10}$ erosion value predicted from Eq. [1] was multiplied by 1.0757 before taking the antilog. The results of the analyses provide the probability of annual fill slope sediment yields as a function of ground cover density for any given year (Fig. 2).

Adjustment for Slope Lengths and Gradients

Wischmeier and Smith (1978) showed that both slope length and slope gradient influence erosion. They used the product *LS* in the Universal Soil Loss Equation (USLE) to correct for slope length (factor *L*) and for slope gradient (factor *S*). However, neither slope length nor slope gradient appear in Eq. [1]. The fixed plot length in our study was 4.6 m and is typical of average fill slope lengths in the mountainous Idaho Batholith. For example, the average fill slope length of all roadfills on the 2 km of the study road was 4.8 m. There is a need to adjust for variable slope lengths, however, because lengths of individual roadfills varied greatly, ranging from less than 1 m to 20 m. Sampled fill slope gradients were consistently steep in the present study because of the steep hillslopes in the area. However, more gentle terrain in other locations of the Idaho Batholith makes it desirable to provide a means to adjust for variable slope gradients as well.

The slope length component of the USLE derived by Wischmeier and Smith (1978) showed erosion rates varying by the square root of $(L_f/22.1)$, where L_f is plot length in meters. However, a recent review of slope length effects by McCool et al. (1989), suggests that the square root exponent is not appropriate. Rather, they provide tabular data expressing the exponent as a function of slope gradient and the ratio of rill to interrill erosion. The data provided for the situation where rill erosion is high relative to interrill erosion are most appropriate for granitic roadfills. Regression analysis was used to fit a hyperbolic model to the McCool et al. data for the high rill/interrill ratio case for slope gradients in excess of 5°. The revised slope length relationship can be computed as

$$L = (l_f/22.1)^k \qquad [2]$$

where

L = slope length factor (dimensionless)
l_f = road fill length (m)
$k = 0.856 - (1.034/s_f)$
s_f = gradient of the roadfill (degrees) for slopes greater than 5 degrees

In another paper, McCool et al. (1987) evaluated the effects of variable slope gradients on soil erosion. They showed that the original slope vs. erosion relationship for S proposed by Wischmeier and Smith (1978) was not appropriate for steep slopes and disturbed soils. Instead, they recommended a relationship of the form

$$S = a + b\,(\sin s_f) \qquad [3]$$

where

S = the ratio of erosion for the gradient of the roadfill slope in question to the erosion for a fill slope gradient of 5.1°
s_f = the slope gradient (degrees) of the roadfill in question and a and b are fitted parameters

McIsaac et al. (1987) evaluated slope steepness effects on soil specifically from disturbed lands such as mined lands and construction sites. They cite only one reference that applies to steep roadfills. This was work done by Israelsen et al. (1980), who evaluated sediment yields from simulated road fill slope gradients of 5.1, 14.0, 26.6, and 40°. Tests were conducted using a rainfall simulator on a tilting erosion plot frame measuring 0.3 m deep, 5.9 m long, and 1.2 m wide. Two of the soils tested could not be used; one was artificially compacted and showed inordinately high erosion rates, and the second consisted of washed sand that showed almost no erosion regardless of slope gradient. The remaining two tests were conducted on silty clay loam and gravelly clay loam soils using variable EI values ranging from 226 to 549 MJ mm/ha h. We ran an analysis of covariance on the data and found that plot slope had a statistically significant effect on erosion ($P = 0.002$), but EI and soil type did not ($P = 0.30$ and 0.26, respectively). Given that there were no statistically significant differences between soils or EI, Eq. [3] was fitted to the Israelsen et al. original data, using the average of the two soils and the three EI values for each of the four slopes classes. Nonlinear regression was used to force the value of S to equal 1.0 at a slope of 5.1°. The result was

$$S = 14.0\,(\sin s_f) - 0.24 \qquad [4]$$

The r^2 value for the relationship was 0.83. The coefficient for b of 14.0 is within the range of values recommended by McIsaac et al. (1987) and is close to the value of 16.8 recommended by McCool et al. (1987).

Applying Eq. [4] to the average fill slope gradient of 37° used in the present study, sediment yields for other roadfill lengths and gradients can be obtained from

$$E_f = L \times S \times E_p \times 0.45 \qquad [5]$$

where

E_f = annual sediment yield for the roadfill slope in question (Mg/ha yr)
E_p = sediment yield predicted from Eq. [1] for roadfills with a slope gradient of 37° and a length of 4.6 m and a given value of ground cover density (Mg/ha yr)
S = S value calculated from Eq. [4]
L = the L value calculated from Eq. [2]

DISCUSSION

Equation [1] provides a simple way to estimate sediment yields from surface erosion on roadfills utilizing commonly accepted variables of EI and GCD. However, at 0.55 the r^2 value for the regression analysis is relatively low. Although not unacceptable, an r^2 of 0.55 does raise some concern because 45% of the variance in sediment yield remains unexplained. We are aware of limitations in the study procedures that probably account for some of the unexplained variance. First, we were unable to obtain concurrent measurements of sediment yields and ground cover density on the study plots because of personnel constraints. Rather, the sediment yield measurements were made in late May–early June and late September–early October, whereas the ground cover density data were collected in August. Accordingly, we had to match the summer soil cover data with both the spring and fall sediment yield data in the analysis. Also, the presence of surface rock material has been shown to reduce erosion (Meyer et al., 1970) and this factor was not included in the determination of GCD. Finally, we were unable to obtain actual storm EI data for individual plots. Instead, we averaged the storm EI data from the five raingauges along the study road. Considering that the study plots were along about 2 km of road, it is likely that average EI values may not provide a good representation of actual EI values on individual plots, especially during the summer when localized convective storms are common. On balance, we advocate the use of the sediment yield prediction equation in spite of the somewhat low r^2 value because (i) the extenuating factors described above would probably help reduce the unexplained variance had we accounted for them, and (ii) the overall regression relationship is highly significant as are both of the independent variables.

Numerous studies have documented an inverse relationship between erosion and amounts of vegetative cover on granitic soils (Renner, 1936; Packer, 1951; Meeuwig, 1969; Bethlahmy, 1967; Megahan, 1978). A similar relationship was found in the present study and is particularly useful, because it includes the effects of both vegetation and surface mulches. Thus, the effects of natural vegetation growth and litter accumulations plus artificial mulching were evaluated. The variables of slope azimuth, direct beam radiation, and elevation were included in the analysis to help index the potential of each road plot for vegetation growth. We felt this might help augment the variance explained by the GCD variable, which included soil cover from both mulches and vegetation. Apparently, this was not the case.

Slope gradient and length have been shown to be important factors influencing erosion rates on roadfills (Israelsen et al., 1980; Burroughs and King, 1989). However, these factors were not significant variables in the present study, because the gradients of the study plots were consistently steep and bordered plots were used. Recent studies by McCool et al. (1987), McIsaac et al. (1987), and Israelsen et al. (1980) to update the slope gradient component of the USLE and by McCool et al. (1989) to update the slope length component of the USLE were adapted to the results of the present study to make it possible to estimate sediment yields for other fill slope gradients and lengths. Data used to adapt these relationships to the steep slopes in the present study are sketchy, and estimates of adjustments for different slope gradients and lengths should be considered approximations.

Additional analyses to define the probability distribution of annual rainfall erosivity for the study area made it possible to predict the probability of annual sediment yields from road fills. In practice, a forest manager can evaluate the probability of annual sediment yields for various levels of ground cover density using Fig. 2. Estimates of sediment yields from roadfills with different slope lengths and slope gradients can be obtained from Eq. [2], [4], and [5]. If the erosion risk is unacceptable, the manager can then take whatever action is necessary to reach an acceptable level of erosion. Possible remedial measures include practices to increase ground cover density such as seeding, transplanting, and mulching (Burroughs and King, 1989; Megahan et al., 1990, unpublished manuscript) or trapping sediment below the road with forest debris or other means (Cook and King, 1983). Additional options to regulate fill slope sediment yields require regulation of fill slope lengths or gradients by modifying the road design or changing road locations. Such analysis techniques fill an important need for forest managers who are required by federal law to deal with cumulative watershed effects in the area.

Results from this study help to explain what causes the time trends in road erosion reported by others in this general area (Megahan, 1974; King, 1984). Much of the first over-winter erosion appears to be the result of mass erosion processes on the fresh, unconsolidated embankment material. Subsequent erosion is primarily from surface erosion processes including raindrop splash, rilling, and dry dreep and is primarily a function of variations in rainfall erosivity and ground cover density. Normally ground cover density increases over time as vegetation grows, litter accumulates on the surface, and surface rock increases as fines are eroded away. Surface rock was not included in the measurement of GCD in the present study. However, trends in the vegetative components of GCD illustrate the time trend process. Measured values of GCD increased from an average of 17% during the first summer after construction to 51% during the third summer. Assuming constant EI over the same time sequence equivalent to the average for all five measurement periods, this increase in GCD would result in an average reduction in erosion of 53%.

There are limitations in the use of the model. Use should be constrained to similar soil and climatic conditions. Also, in the present study, drainage from the road surface was completely controlled by cross drains and berms, once the road was completed to design specification. Thus, there was no additional erosion on fill slopes caused by runoff from the road travel surface or cut slopes. Most forest roads constructed on granitic soils are insloped to prevent road runoff flow on fillslopes. Estimated sediment yields will have to be increased accordingly in areas where this is not the case. Carlton et al. (1982) reported about 10 times more erosion on roadfills subjected to road runoff compared to fill sections where road runoff was prevented.

One final caveat is necessary. The predicted sediment yields from Eq. [1] and Fig. 2 do not include the high first year over-winter erosion characteristic of these steep mountain areas, because erosion rates on the steep, unconsolidated roadfills are exacerbated by mass erosion processes during this time. Allowance for the first year over-winter erosion is considered in the road design by forest engineers working in the area and is the basis for the "slough widening" commonly included in the design road width. For the eight plots where first year over-winter data were available, there was a factor of about five times more sediment yield during the first winter compared to the average of the subsequent five summer-winter periods. Until more information is available to better predict the influence of mass erosion processes on sediment yields during the first winter following construction, this factor can be used to estimate first year over-winter sediment yields relative to the average sediment yields for the subsequent 2.5 yr.

CONCLUSIONS

Seasonal sediment yield data from 29 erosion plots were used to evaluate the influence of site factors on sediment yields from granitic roadfills in the Idaho Batholith. The only statistically significant factors influencing sediment yields were ground cover density and the erosivity index component of the Universal Soil Loss Equation applied to snowfree periods of the year. A prediction equation based on ground cover density and snowfree period erosivity index explained 55% of the variance in sediment yields.

We analyzed 22 yr of data from six ARS raingauges in the vicinity to show that snowfree period erosivity index values were log normally distributed. Parameters for the log normal distributions were not related to raingauge elevation, suggesting that mean values of the parameters could be used.

A Monte Carlo procedure was used to simulate sediment yields from roadfills based on the prediction equation developed from the erosion plots and the probability density function of snowfree period erosivity index. A total of 5000 estimates of annual sediment yields was generated for each of 10 levels of ground cover density ranging from 5 to 90%. The resulting data were summarized in Fig. 2 to show the probability of annual sediment yields from roadfills for varying levels of ground cover density.

Effects of variations in fill slope gradient and length were not directly evaluated in the present study because the fill slopes sampled were uniformly steep and bordered plots were used. However, study results were adapted to varying slope lengths and gradients based on recent updates of the Universal Soil Loss Equation that deal with the effects of varying slope gradients and slope lengths.

Roads associated with forest management activities are the primary cause of serious downstream cumulative effects from sedimentation in the Idaho Batholith. The probabilistic approach for predicting and reducing sediment yields from roadfill slopes developed here provides a useful tool for forest land managers to manage such cumulative effects. In cases where risks are unacceptable, options available to land mangers to reduce sediment yields include increasing ground cover densities using mulches or revegetation or both, and reducing fill slope lengths or gradients by changing the road design or road location.

There are limitations in the use of the sediment yield estimation procedure. Use should be restricted to similar soil and climatic conditions. Also, the procedures for extrapolating erosion predictions to other fillslope lengths and gradients are based on sketchy data. Additional research is needed to check the reliability of the derived relationships. Finally, the procedure does not apply to outsloped road design where water from the road surface is allowed to run over the surface of roadfills, not is it applicable to the first winter after road construction, when a large proportion of the erosion is occurring from mass erosion processes.

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